

Hybrid Gear Performance Under Loss-of-Lubrication Conditions

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ABSTRACT

Hybrid composite gear technology is being investigated to increase power density in rotorcraft drive systems. These gears differ from conventional steel gears in that the structural web material is replaced with a lightweight carbon fiber composite. Past studies have focused on performance of this technology under normal operating conditions, however, for this technology to be viable it must also withstand adverse conditions. The study presented here evaluates the performance of hybrid gears under loss-of-lubrication conditions in NASA Glenn Research Center's Contact Fatigue Test Facility. Two experiments are presented using small-scale 3.5 inch (8.9 cm) pitch diameter hybrid gears and compared to a baseline steel gear pair. Results of these tests show that there are limitations to the use of a hexagonal interlock pattern between the steel and composite. There is also evidence that the presence of polymer in the gear during an oil out event has a potential to increase time to failure. Further studies are planned to expand on these initial findings.

**** This paper has been corrected from the original submitted to the conference. ****

INTRODUCTION

The civil and military rotorcraft communities are consistently striving to reduce drive system weight and increase power density. Past government-funded research and technology development efforts have used power density as the most critical performance metric (Ref. 1, 2). In recent years, composite materials have been considered for use in drive system components as a means of reducing component weight (e.g. housings, drive shafts, and gears) (Ref. 3, 4). NASA Glenn Research Center has partnered with the Army Research Laboratory to investigate hybrid composite gears as a means of reducing gear weight specifically in rotorcraft transmissions.

In hybrid gear technology, the structural portion of the gear (between the teeth and the shaft interface) is replaced with a lightweight carbon fiber composite. Several past experiments have been performed to investigate hybrid gear performance and durability (Ref. 5, 6, and 7), including static torsion, operational, and vibration experiments. These experiments were performed on both small-scale 3.5-in (8.9 cm) and full-scale 16.5-in (41.9 cm) pitch diameter gears (Ref. 5, 6, 7). Operational experiments to date have focused on operation in a normal gearbox environment and did not investigate operation under adverse conditions.

The drive system of all military rotorcraft must satisfy several qualification tests according to the Aeronautical Design Standard ADS-50-PRF (Ref. 8). One of the many required qualification tests is an oil-out or loss-of-lubrication test, where the gearbox must continue to operate for at least 30 minutes after a low lubricant level warning. Being perhaps the harshest of the qualification tests to pass, it is important that any new advanced drive system components, such as the described hybrid composite gear, be able to survive the high temperatures associated with such an event. The study presented in this paper investigates the performance of hybrid composite gear technology under loss-of-lubrication conditions in two separate small-scale experiments.

HYBRID GEAR DESIGN

The hybrid gears manufactured for this study followed the process as described in Ref. 1, however, a brief description of the process is provided here. In the hybrid composite gear concept, the structural web portion of a steel gear is replaced with a lighter weight carbon fiber composite. The gears used for this particular study were made from standard NASA 3.5 inch (8.9 cm) pitch diameter spur gears that had already been ground and heat treated. These gears were made of AISI 9310 gear steel and had the gear properties shown in Table 1.

Turning these aerospace quality gears into hybrid gears involved removing the structural material between the gear hub (which interfaces with the shaft) and the gear teeth, leaving a hexagonal pattern in the steel components. The removed web material was then replaced with a lightweight

carbon fiber composite material. Additional composite material was used on either side of the gear to capture the composite web material axially (See Fig. 1). For this study, the composite material was made using a (0°/+60°/-60°) braided prepreg and compression molding. T700 carbon fiber was utilized with a Cytec MTM45-1 matrix. Additionally, a Cytec MTA241 film adhesive was used to bond the axial interface between steel and composite parts. A total of 36 layers of composite material were assembled and cured in a specialized fixture at a final temperature of 177 °C (350 °F). The fixture for fabrication and curing used the inner diameter of the hub and the gear measurement over pins to keep the gear teeth aligned with the axis of rotation.

Table 1. Basic test gear data (Ref. 5)

Characteristic	Value
Number of teeth	42
Diametral pitch, 1/in (Module, mm)	12 (2.12)
Circular pitch, in. (mm.)	0.2618 (6.650)
Whole depth, in. (mm)	0.196 (4.98)
Addendum, in. (mm)	0.083 (2.11)
Chordal tooth thickness, in. (mm)	0.1279 (3.249)
Pressure angle, degrees	25
Pitch diameter, in. (mm)	3.5 (89)
Outside diameter, in. (mm)	3.667 (93.14)
Backlash, in. (mm)	0.006 (0.15)
Tip Relief, in. (mm)	0.0005- 0.0007 (.013-.018)

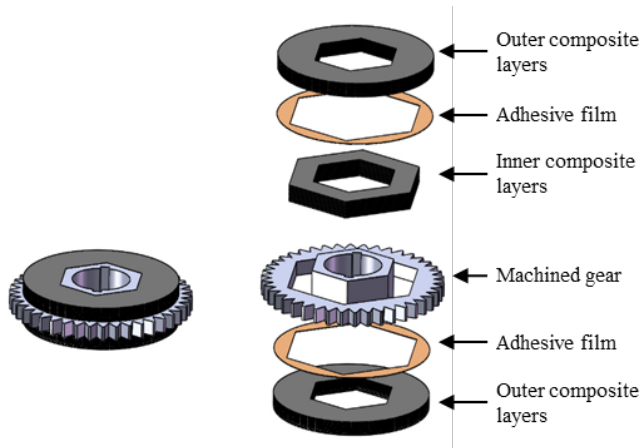


Figure 1. Hybrid composite gear design.

Due to the discrepancy in the coefficient of thermal expansion between the composite, 1.7×10^{-6} 1/°F (3.0×10^{-6} 1/°C), and steel, 7.3×10^{-6} 1/°F (13×10^{-6} 1/°C), there was significant distortion in the gear teeth after curing. This resulted in enough runout and tooth profile distortion that the mating gears were difficult to rotate through mesh with no apparent backlash. The gears were reground to the correct tooth form, resulting in an increase in backlash, 0.008-0.010 in. (0.20-0.25 mm), over the normal 0.006 in. (0.15 mm).

EXPERIMENTAL SETUP

The experiments performed in this study utilized the NASA Glenn Contact Fatigue Test Facility, modified to accommodate loss-of-lubrication experiments (Ref. 9, 10). A sketch of the rig used for these experiments is shown in Fig. 2. This gearbox operates in a closed-loop, torque regenerative fashion with a rotating torque actuator located in the right side slave gear. When hydraulic pressure is applied against the load vane, the actuator twists the right hand slave gear with respect to the right hand test gear, thus locking torque in the loop. The total rotation between the right side shaft and the slave gear is 20° before hitting the end of the cavity on either side. Facility speed and hydraulic load can be varied as needed during the experiment. The test gears have a 1:1 gear ratio.

The test side of the gearbox was outfitted with three thermocouples: one adjacent to both the right and left gears on the outside of the gearbox (away from the mesh), and one located just out-of-mesh as shown in Fig. 3. The out-of-mesh thermocouple was mounted to the front cover of the gearbox and is not shown in the figure. These thermocouples were used to monitor the air-oil temperature adjacent to the rotating gears.

Loss-of-lubrication testing in this facility is generally performed with axial and radial shrouding to help prevent expelled oil on the housing from dripping into the mesh. However, these shrouds would not accommodate the hybrid gears due to the increased width and therefore were not used in this study.

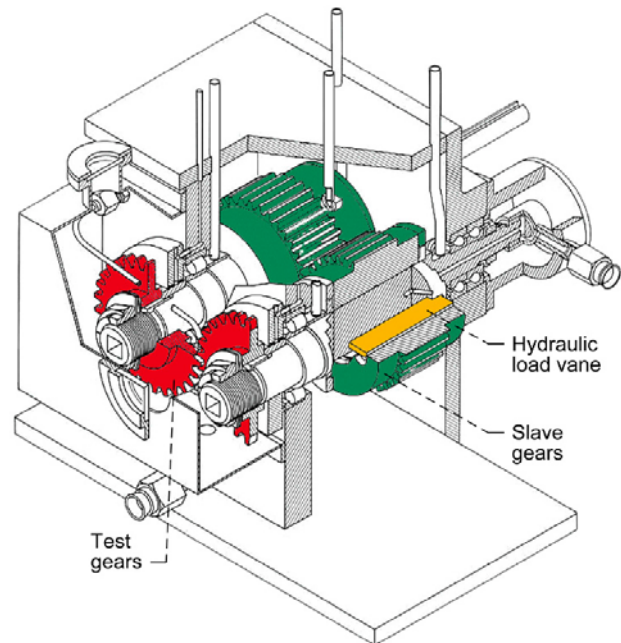


Figure 2. Cross-sectional sketch of the experimental setup used for loss-of-lubrication testing.

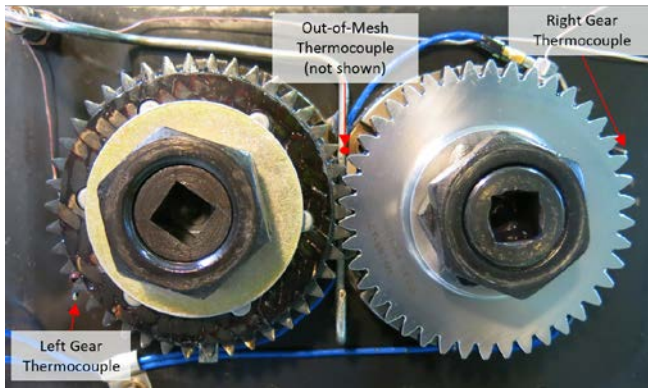


Figure 3. Gearbox instrumentation diagram.

The experimental procedure for this study included a run-in period with normal lubrication for a minimum of one hour at 10,000 RPM with 210 in-lbs (24 N-m) of torque. Torque was then increased to 520 in-lbs (59 N-m). Once at a stable run condition, the oil supply to the gearbox was disconnected and capped to prevent oil from being siphoned from the supply line. The experiment was continued until major surface damage occurred, which was indicated by thermal runaway, red glowing gear teeth, and/or sparks within the gearbox, with some deviation as described below.

RESULTS

Loss-of-lubrication Experiment 1

Results from the initial hybrid gear loss-of-lubrication test are shown in Fig. 4, from the point at which the oil supply was disconnected to the end of the experiment. For this experiment, a hybrid gear was driving another hybrid gear and the experiment ran significantly longer than previously performed steel gear experiments with the same pitch (Ref. 10). The temperature data displays an initial increase associated with the lubrication supply being shut off, followed by a plateau. Between 50 and 250 minutes, there were several fluctuations in the temperature, however, none of these fluctuations resulted in thermal runaway or plastic deformation of the gear teeth. At 250 minutes, the test was discontinued. After shutdown, the pressure to the loading mechanism was restored. With torque locked in the loop, the rig cannot normally be rotated by hand, however, in this case the rig rotated freely suggesting a loss of torque. The cavity of the hydraulic load mechanism allows for a total rotation between the slave gear and shaft of 20 degrees. Applying load pressure when the vane has already reached its furthest position within the cavity does not result in further applied torque. Therefore, the gear teeth likely rotated enough with respect to the inner hub for the vane in the load mechanism to reach its maximum angle of rotation, limiting the total torque locked in the mechanical loop.

The hybrid gears are assembled such that the vertices of the hexagonal interlock on the inner metallic adapter point radially outward to the center of a gear tooth. Post-test visual inspection of the left gear, referred to here as Hybrid Gear 1 (HG1), showed that the inner hub hexagonal pattern

pointed to a tooth space. The outer composite layer on one side of HG1 was removed to inspect the interlock pattern. It appears that the higher coefficient of thermal expansion of the steel relative to that of the composite allowed a gap to form between the steel rim and composite web at the highest temperatures during the experiment. This resulted in a relative rotation of the rim with respect to the web (clockwise rotation of the rim in Fig. 5). After rotation, contact stresses between the outer part of the composite web and the inner part of the steel rim become localized compressive stresses on the left side of each outer vertex point of the hexagonal web. There is some evidence of local compression failure of the composite material near these high stress concentration regions.

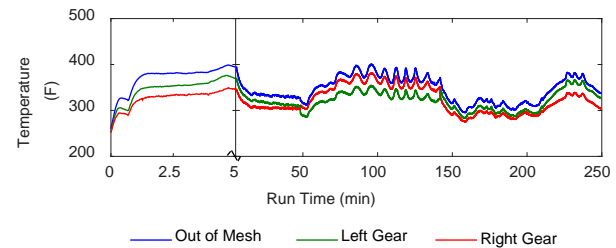


Figure 4. Temperature data from the first hybrid gear loss-of-lubrication experiment.

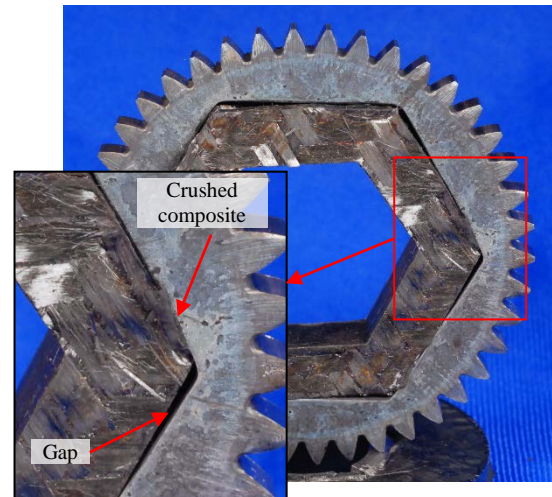


Figure 5. Post-test photo of disassembled hybrid gear 1.

Loss-of-lubrication Experiment 2

With no damage to the mating gear during experiment 1, hybrid gear 2 (HG2) was reused for an additional experiment. HG2 was altered to include an array of six 0.313 inch (7.94 mm) pins, in an effort to reduce the likelihood that a similar angular rotation would occur between the inner and outer metallic components. The pins were installed such that they were located at the thickest part of the outer steel ring (that contains the gear teeth) with the center of the pin being located at the interface between the composite and steel (see Fig. 6). This experiment was

performed such that the load was applied to the opposite side of the teeth from experiment 1 and against standard steel gear as shown in Fig. 3, with a backlash of 0.009 inches (0.23 mm).

The data from the second hybrid gear loss-of-lubrication experiment is shown in Fig. 7. The experiment started out similarly to the first, with a sudden increase in temperature followed by a plateau. At approximately 45 minutes, the experiment was stopped in order to verify that torque was being applied to the gear. At this time, a visual inspection of the gear was also performed and black radial lines were noted on the HG2 gear teeth. Photos were taken at this point for documentation purposes.

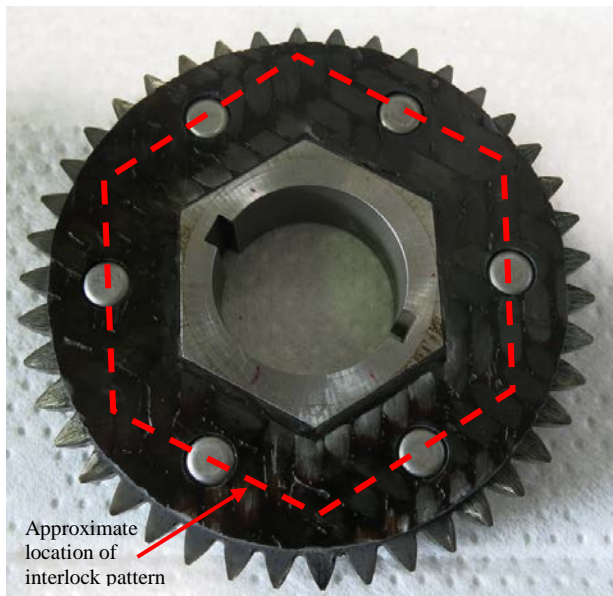


Figure 6. Modified “pinned” hybrid gear 2 prior to experiment 2.

The experiment was then continued, starting up under dry conditions and light load. Once at 10,000 RPM, torque was then reapplied. Approximately 20 minutes after restarting the experiment (66 minutes of total run time), a spike in temperature was experienced, however, after reaching a peak out-of-mesh temperature of 467°F (242°C) the temperature started to decrease similar to the oscillation behavior seen during experiment 1. At 72 minutes of combined run time, the torque was increased to try to force thermal runaway. This resulted in a similar peak in the out-of-mesh temperature, followed by another decrease. The rig was shut down at 83 minutes to verify once again that torque was still being applied and to perform another visual inspection.

At this point, significant black material was found on the hybrid gear teeth. This material found was once again arranged in radial lines, suggesting to the authors that some part of the hybrid gear was softening due to increased temperature and then being flung radially outward. The black substance was photographed prior to resuming the

experiment. Once again, the rig was started up dry under light load and then the full load was applied after reaching 10,000 RPM. An additional temperature oscillation occurred up to a maximum out-of-mesh 447°F (231°C).

At a combined run time of 96 minutes, the torque was once again increased, this time to approximately 740 in-lbs (84 N-m). This resulted in a peak in air-oil temperature at the out-of-mesh location of 474°F (246°C) followed by another decrease. Two additional small temperature variations were experienced before the experiment was discontinued at 145 min. After the experiment was discontinued, torque transfer was once again verified.

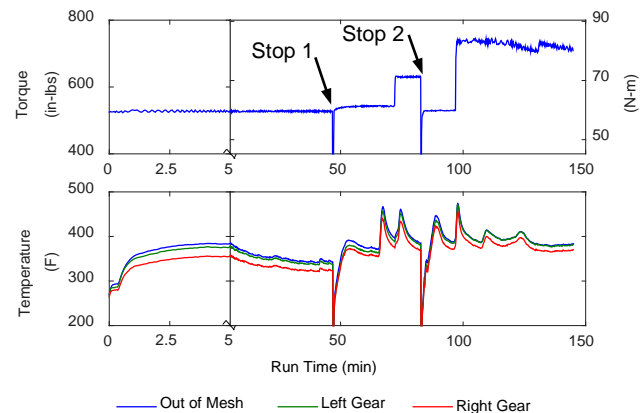


Figure 7. Data from the second hybrid gear loss-of-lubrication test.

Photographs of the black substance on the gear teeth described above are shown in Fig. 8. Each photograph was taken at a different stopping point during testing: at 45 min (a), 83 minutes (b), and 145 min (c). The increase in the presence of black material can be seen here, particularly between 45 and 83 minutes of cumulative run time. At the completion of the experiment, there were several locations around the gear where this substance extended radially past the edges of the tooth and re-hardened.

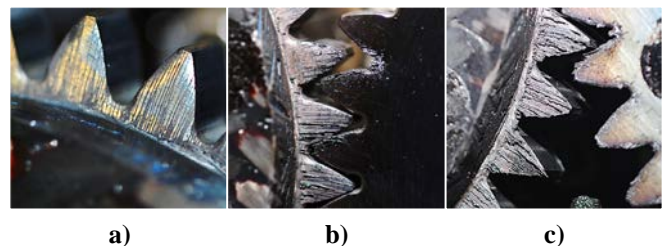


Figure 8. Black debris found on gear teeth during test 2 at (a) 45, (b) 83, and (c) 145 minutes of cumulative run time.

For reference, a baseline experiment was performed using two steel gears made of 9310, from the same lot that the hybrid gears were manufactured. While steel gears are

generally run in a shrouded configuration, this particular experiment was run without shrouding to match the hybrid gear experiments. The experiment was performed using the same procedure as the previous experiments and included a rise and plateau in temperature up to approximately 2 minutes (see Fig. 9). At this point, the temperature began to increase resulting in plastic deformation of the gear teeth and a loss of transmitted torque at just over 2.5 minutes. A photograph of the gear teeth taken after the experiment is shown in Fig. 10.

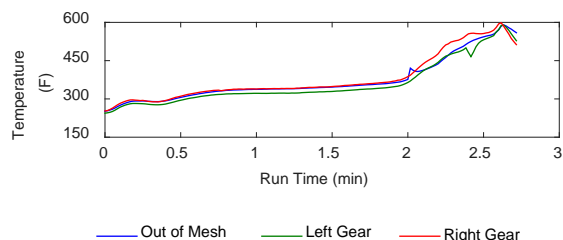


Figure 9. Baseline steel gear temperature data.

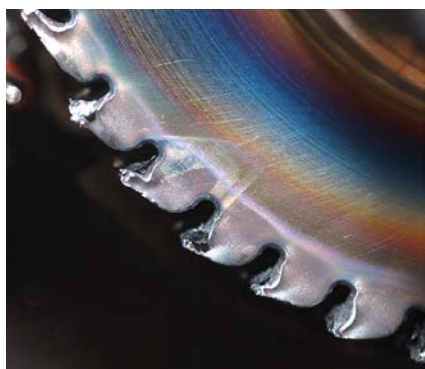


Figure 10. Baseline gear teeth after loss-of-lubrication experiment.

Post-test Analysis

In an effort to verify the source of the black substance from experiment 2, samples were collected from the teeth of HG2 and from inside the gearbox housing. These samples were analyzed using energy dispersive spectroscopy (EDS) on a scanning electron microscope, providing an elemental characterization of the sample. In addition to samples of the debris, samples of the prepreg composite and thin film adhesive were also analyzed.

Figure 11 shows the elemental analysis of one of the radial lines of black material scraped from a tooth, which identified the presence of carbon, oxygen, and sulfur as well as a trace amount of iron. Analysis of the residue found in the gearbox identified a larger amount of iron in addition to sulfur, oxygen, and carbon (Fig. 12). Both the epoxy on the prepreg and the thin film adhesive contain carbon, oxygen and sulfur as the major components (Fig. 13 and 14). The blue box indicates the areas of analysis in each image. Since the oil used during run-in for these gears does not contain

sulfur, the black substance on the gear teeth likely originates from either the epoxy matrix or the thin film adhesive.

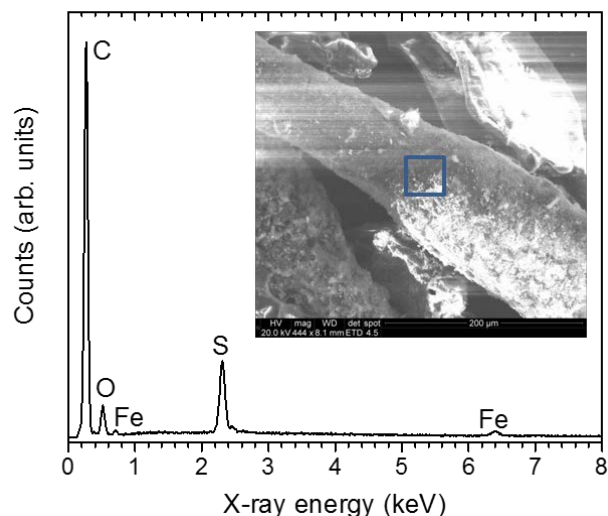


Figure 11. EDX analysis of black tooth substance.

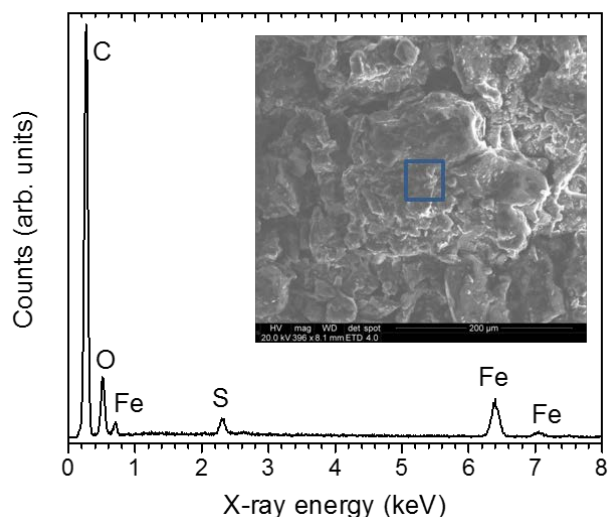


Figure 12. EDS analysis of gearbox residue.

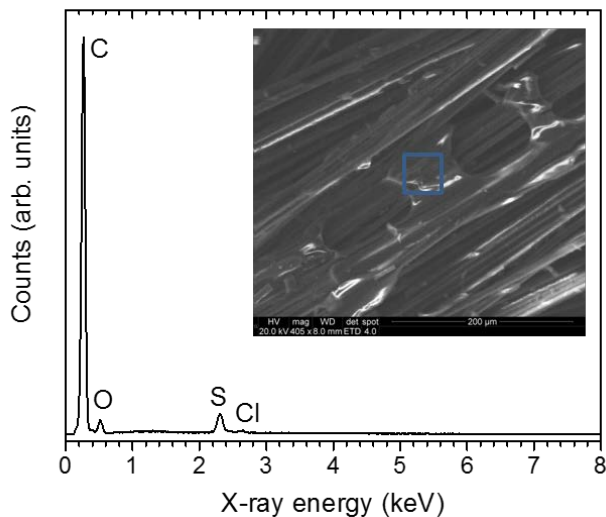


Figure 13. EDS of epoxy on prepreg composite.

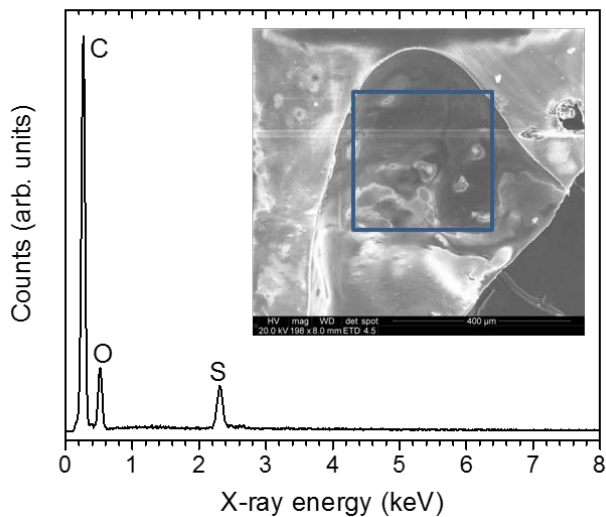


Figure 14. EDS of thin film adhesive.

CONCLUSIONS

Two hybrid gear loss-of-lubrication experiments were performed as part of this study. Based on the results of these experiments, the following conclusions are made.

First, experiment 1 resulted in both a failure of the adhesive bond layer and crushing of the internal composite interlock, likely due to the difference in the coefficients of thermal expansion between the steel and composite. Therefore, the hexagonal mechanical interlock pattern is a potential weak link that must be considered in hybrid gear design, when operating under the high temperature conditions associated with a loss-of-oil event. Different mechanical interlock patterns, such as the pinned arrangement used in experiment 2, exist that better withstand the high temperature conditions associated with this type of event.

Given a mechanical interlock that can withstand this type of event, there is a possibility that the presence of polymers in the thin film adhesives and/or the composite matrix may provide a source of lubricant at high temperatures. The authors suspect that when the composite and/or film adhesive get hot enough, they start to soften and under the right conditions are flung radially outward. If this softened polymer enters the mesh, it may act as a lubricant or sulfur-containing lubricant additive to allow for extended running under dry conditions. It should also be considered that the loss of polymer from the matrix or film adhesive could potentially undermine the structural integrity of the gear, though this was not experienced during experiment 2.

Future work will further isolate the reasoning behind the extended runtime during experiment 2. While the authors expect that the polymer flow observed provided lubrication to the gear mesh, there is also a chance that the increased backlash due to the regrinding process may have increased performance. Future experiments are planned to investigate increased backlash during loss-of-lubrication on a conventional steel gear pair. Additionally, the authors plan to investigate whether this polymer flow phenomenon can be extended to conventional steel gears to increase survivability during an oil-out event.

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